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A PHYSICAL UPPER LIMIT ON THE H I COLUMN DENSITY OF GAS CLOUDS

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ABSTRACT

An intriguing fact about cosmic gas clouds is that they all appear to have neutral (atomic) hydrogen column densities smaller than 10^{22} cm^{-2}. Observations of damped Lyα (DLA) absorption systems further indicate that the maximum N_{HI} decreases with increasing metallicity. It is generally assumed that this trend is due to a dust-induced selection bias: DLA systems with high N_{HI} and high metallicity contain so much dust that the background QSO becomes too dim to be included in optically selected surveys. Here, it is argued that this explanation may not be viable. Instead, it is proposed that conversion to molecular hydrogen determines the maximum H I column density. Molecular hydrogen forms on the surface of dust grains and is destroyed by photodissociation. Therefore, the molecular fraction correlates with both the dust content and, because of self-shielding, the total hydrogen column density, and anticorrelates with the intensity of the incident UV-radiation. It is shown that the first relation can account for the observed anticorrelation between the maximum N_{HI} and metallicity.

Subject headings: galaxies: formation — galaxies: ISM — intergalactic medium — ISM: clouds — ISM: molecules — quasars: absorption lines

1. INTRODUCTION

Hydrogen is the most abundant element in the universe and consequently the total hydrogen content is one of the most basic characteristics of gas clouds. Hydrogen is most easily observed in atomic, neutral form through the Lyα (1216 Å) or the 21cm transition, either in absorption or emission. Because the line-of-sight extent of a gas cloud is difficult to measure and because the transverse size is generally unknown in case of absorption studies, it is not the mass, but the column density that is the main observable quantity characterizing the total gas content of a cloud. Perhaps the most basic observation about the distribution of neutral hydrogen column densities is that clouds with $N_{HI} > 10^{22}$ cm^{-2} (> 80 M$_\odot$ pc^{-2}) appear to be extremely rare, if they exist at all.[1]

A well-known, possible explanation for the observed cut-off in the distribution of absorption line column densities is selection bias: if the dust-to-gas ratio is roughly constant, then higher column density clouds contain more dust, leading to a stronger extinction of background sources. Thus, the presence of dust may cause sight lines through high column density clouds to be missing from magnitude limited surveys (e.g., Ostriker & Heisler 1984; Wright 1990; Fall & Pei 1993). If dust-bias is important, then there should be an anticorrelation between the maximum column density and the dust-to-gas ratio (and hence metallicity Z) of gas clouds. Damped Lyα (DLA) systems, i.e., absorbers with $N_{HI} > 2\times10^{20}$ cm^{-2}, do indeed show such an anticorrelation: Boissé et al. (1998; see also Prantzos & Boissier 2000) found that observed DLA systems satisfy $[\mathrm{Zn/H}]+\log(\mathrm{N_{HI}}) < 20.5$ and interpreted this as a dust-induced selection effect.

The presence of dust in DLA systems has been established using two independent types of observations. First, it has been shown that QSOs with DLA systems in the foreground appear redder than those without DLA systems in the foreground (Fall, Pei, & McMahon 1989). Second, the relative abundances of refractory elements, such as chromium and iron, are significantly lower than those of elements such as zinc, which are thought to be only lightly depleted on dust grains (e.g., Pettini et al. 1997a).

Although dust seems to be present in at least a subset of DLA systems, the idea that dust-bias can explain the absence of high N_{HI}, high Z systems faces at least three potential problems. First, 21cm emission line studies of nearby galaxies do not reveal higher H I column densities than are found in absorption line studies. Radial profiles of the neutral hydrogen surface density of disk galaxies generally show a maximum value of $\max(N_{HI}) \lesssim 10^{21}$ cm^{-2} ($\lesssim 8$ M$_\odot$ pc^{-2}) and always less than 10^{22} cm^{-2} (e.g., Cayatte et al. 1994; Rhee & van Albada 1996). Second, preliminary results from the survey of radio-selected QSOs by Ellison et al. (2001), which is free from the dust-bias that affects optically selected samples, do not provide evidence for a previously unrecognized population of $N_{HI} > 10^{21}$ cm^{-2} absorbers. Third, the metallicities and dust-to-gas ratios of DLA systems are typically more than an order of magnitude below the Galactic values (e.g., Pettini et al. 1997a, 1997b) and Prochaska & Wolfe (2001) have argued that the implied extinction corrections are far too small to explain the obscuration threshold proposed by Boissé et al.

In this letter, a simple physical explanation for the cut-off in the distribution of H I column densities is proposed. Although the total hydrogen column density of a gas cloud will always increase as its density increases, the same is not true for the neutral hydrogen column density. As the (column) density increases, the fraction of hydrogen in molecular form increases and eventually the H I column density will stop increasing. Furthermore, the cross section for DLA absorption provided by self-gravitating clouds with high molecular fractions is low because such clouds are compact and unstable to star formation. Because hydrogen molecules are formed on the surface of dust grains, the molecular fraction correlates with the dust-to-gas ratio (and thus metallicity). Hence, the conversion of H I to H_2 naturally explains the observed anticorrelation between the

[1] In some extreme environments, such as broad absorption line QSOs, hydrogen columns in excess of 10^{22} cm^{-2} have been inferred from soft X-ray absorption measurements (e.g., Mathur, Elvis, & Singh 1995). However, these observations cannot distinguish between atomic and molecular hydrogen.

maximum H I column density and metallicity. In the remainder of this letter it will be shown that this idea works quantitatively.

Earlier, related work on the conditions required for the conversion of H I to H_2 includes Hollenbach, Werner, & Salpeter (1971), Federman, Glassgold, & Kwan (1979) and Franco & Cox (1986).

2. METHOD

In this section I will describe and discuss the method used to derive the maximum neutral hydrogen column density as a function of metallicity for a given dust-to-metals ratio and incident radiation field.

Consider a sight line through a gas cloud of arbitrary shape. Let n_H and L be the characteristic density and size of the absorber. For now, let us assume that the cloud is self-gravitating, i.e., the pressure of the medium external to the cloud is low compared to its central pressure, and supported by thermal pressure. Such clouds will generally be close to local hydrostatic equilibrium, i.e., the characteristic size will be close to the local Jeans length L_J. If $L \gg L_J$, then the cloud will expand or evaporate and equilibrium will be restored on a sound crossing timescale. If $L \ll L_J$, then the cloud is Jeans unstable and will fragment or shock to the virial temperature, equilibrium will then be restored on a dynamical timescale. Schaye (2001a) used this argument to derive the properties of Lyα forest absorbers, to explain the shape of their column density distribution function, and to compute their contribution to the cosmic baryon density. The results agreed very well with both observations and hydrodynamical simulations. Because the densities of interest here are much higher than those of Lyα forest absorbers, the timescales for the restoration of hydrostatic equilibrium are much shorter and hence one would expect that the same argument works at least as well for self-gravitating DLA systems as for Lyα forest absorbers.

In local hydrostatic equilibrium, the total hydrogen column density is given by the following expression (Schaye 2001a)[2]:

$$N_{H,J} \equiv n_H L_J = \left(\frac{\pi\gamma k}{\mu m_H^2 G}\right)^{1/2} (1-Y)^{1/2} f_g^{1/2} n_H^{1/2} T^{1/2}, \qquad (1)$$

where $\gamma = 5/3$ is the ratio of specific heats for a monatomic gas, $Y = 0.24$ is the baryonic mass fraction in helium, f_g is the fraction of mass in gas (excluding stars) and the other symbols have their usual meanings. To be conservative, f_g will be set equal to unity.

For a given metallicity, dust-to-metals ratio and incident radiation field, the neutral hydrogen column density is computed as a function of the density as follows. First, a grid of (N_H, n_H) models is computed using the publicly available photoionization package CLOUDY[3] (version 94; see Ferland 2000 for details), modeling the absorbers as slabs of constant density illuminated from two sides[4]. The temperature is *not* a free parameter. For each model the thermal equilibrium temperature, the mean molecular weight μ, and the neutral hydrogen column density are computed self consistently. Second, the solutions $(N_H, n_H, T(N_H, n_H), \mu(N_H, n_H))$ are selected for which equation (1) is satisfied (i.e., $N_H = N_{H,J}$) and which are stable ($dP/dn_H > 0$). Third, from these solutions the maximum N_{HI} is determined. The whole procedure is then repeated for different metallicities to derive the maximum neutral hydrogen column density as a function of the metallicity.

Figure 1 illustrates the results for a model with metallicity 0.1 solar and a dust-to-metals ratio of 0.5 times the Galactic value, values typical for DLA systems (e.g., Pettini et al. 1997ab; Vladilo 1998). The dust was assumed to have ISM properties and consists of a mixture of graphites and silicates (see the CLOUDY documentation for details). The gas clouds were exposed to the model for the UV/X-ray background radiation at $z = 3$ of Haardt & Madau (2001)[5], which includes contributions from QSOs and galaxies and yields H I and He II photoionization rates of 1.15×10^{-12} s^{-1} and 1.96×10^{-14} s^{-1} respectively.

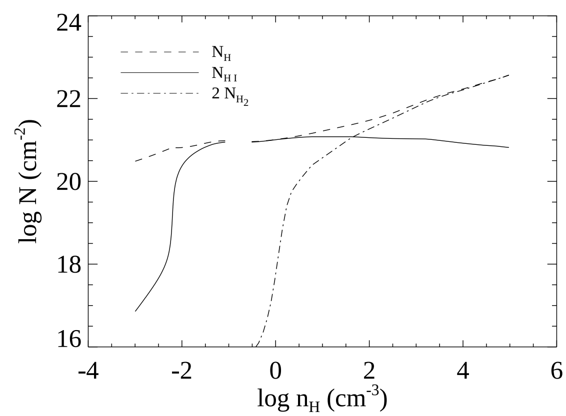

FIG. 1.— Hydrogen column densities as a function of density. The model assumes local hydrostatic and thermal equilibrium, metallicity $Z = 0.1 Z_\odot$, dust-to-metal ratio 0.5 times the Galactic value, and the model for the $z = 3$ UV/X-ray background radiation of Haardt & Madau (2001). There is a gap around $n_H \sim 10^{-1}$ cm^{-2} because there are no stable solutions in this region.

Note that the curves in Fig. 1 do not show the evolution of an individual cloud. Each point along the curves corresponds to a cloud in local hydrostatic and thermal equilibrium, and higher densities correspond to lower cloud masses. If a cloud accretes matter, it will become Jeans unstable and fragment into pieces of higher N_H and lower mass which will again be close to the equilibrium curve. The model clouds become self-shielded at $n_H \sim 10^{-2}$ cm^{-3}. There is a gap at $n_H \sim 10^{-1}$ cm^{-3} because clouds in this range are unstable ($dP/dn_H < 0$). At lower densities the clouds are warm ($T \sim 10^4$ K) and extended ($L \gtrsim 10^3$ pc), while clouds with higher densities are colder ($T \lesssim 10^3$ K) and more compact ($L \lesssim 10^2$ pc). For $n_H \gtrsim 10$ cm^{-3} the clouds are highly molecular and clouds with higher densities have smaller H I column densities. The physical properties of self-shielded, self-gravitating gas clouds will be discussed in more detail elsewhere.

The method described above assumes that the absorbers are self-gravitating, an assumption that may not hold for DLA systems. Indeed, it is well known that the interstellar medium of the Galaxy has a multiphase structure and that H I clouds are generally pressure confined, although molecular clouds are not.

[2]This expression differs by a factor $\pi^{1/2}$ from equation A5 of Schaye (2001a), who performed a purely dimensional analysis. Since this factor is usually included in the definition of the Jeans length, I include it here to obtain a more conservative upper limit on the maximum column density.

[3]`http://www.pa.uky.edu/~gary/cloudy/`

[4]Illumination from two sides is approximated by doubling all column densities of a plane parallel cloud illuminated from one side.

[5]The data and a description of the input parameters can be found at `http://pitto.mib.infn.it/~haardt/refmodel.html`. The cloud is also exposed to the cosmic microwave background and to a cosmic ray density of 2×10^{-9} cm^{-3}, but these have no significant effect on the results.

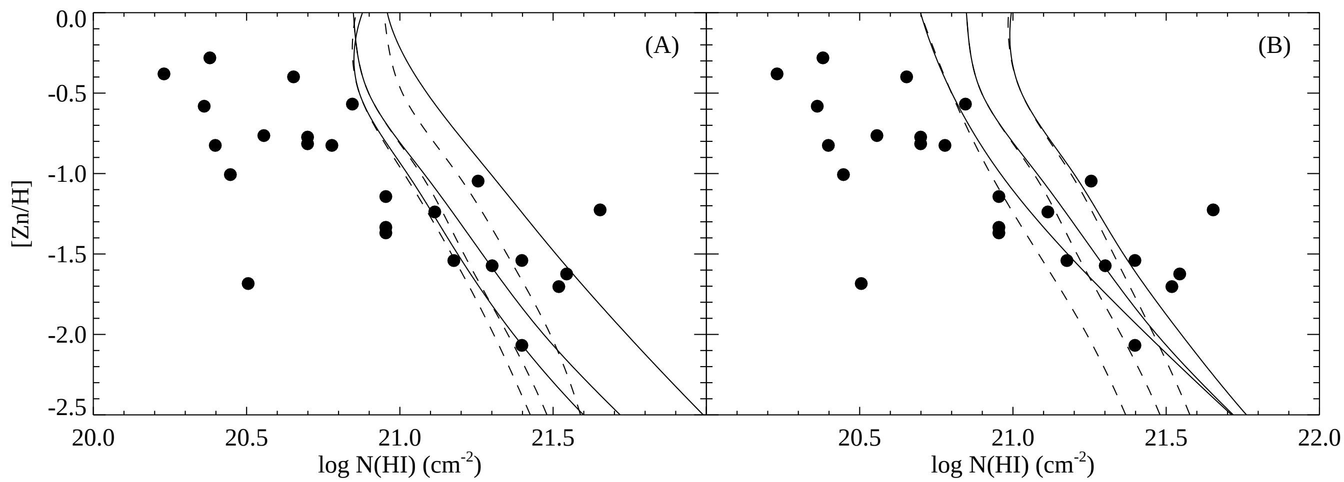

FIG. 2.— Metallicity as a function of neutral hydrogen column density. Model curves indicate the maximum N_{HI} (solid lines) and the H I column density for which the molecular fraction is 10 percent (dashed lines). Panel (a): From top to bottom the curves correspond to a dust-to-metals ratio of 0.1, 0.5 and 1.0 times the Galactic value respectively and the $z = 3$ UV/X-ray background of Haardt & Madau (2001). Panel (b): Curves are for a dust-to-metals ratio of half the Galactic value and the UV/X-ray background used in panel (a) multiplied by, from top to bottom, factors of 3, 1, and 1/3 respectively. Data points are the observed $z \geq 1$ DLA systems taken from Pettini et al. (1997b; 2000), Prochaska & Wolfe (1999), de la Varga et al. (2000), and Molaro et al. (2000). The 1-σ errors are typically about 0.1 dex for both N_{HI} and [Zn/H].

Furthermore, it was recently argued by Schaye (2001a) that at least a subset of DLA systems appear to arise in galactic winds, in which case (ram) pressure is likely to be more important than self-gravity. Fortunately, the possibility that some (or even most) DLA systems are confined by external pressure does not affect the current analysis because a gas cloud with $L < L_J$ will always have a smaller column density than a gas cloud in hydrostatic equilibrium *with the same density*. Pressure-confined solutions will therefore lie below the solid curve in Fig. 1 and the assumption of local hydrostatic equilibrium is thus conservative when estimating the maximum N_{HI}. Recall that self-gravitating clouds containing stars and/or dark matter also have lower column densities.

Higher neutral column densities are possible for clouds that are self-gravitating and for which turbulent or magnetic pressure dominates over thermal pressure, and for clouds that are rotationally supported *and* oriented such that our line of sight is nearly perpendicular to their spin axes. One would, however, expect these caveats to be important mostly for clouds in regions of ongoing star formation. In such regions the ISM is likely to be multiphase and the H I clouds pressure-confined, thus reducing their column densities compared to clouds in hydrostatic equilibrium. Finally, it should be noted that although the integrated column density can be very large for a sight line through an edge-on disk galaxy, this column will generally be the sum of the column densities of a large number of clouds.

3. RESULTS

Figure 2a shows the observed [Zn/H] as a function of N_{HI} for DLA systems with redshift $z \geq 1$. The absence of points in the upper right part of the diagram, indicating a metallicity-dependent N_{HI} cut-off, was first noted by Boissé et al. (1998) who interpreted it as a dust-induced selection bias. The lack of data points in the bottom left part of the figure is most likely a selection effect: the corresponding zinc lines are too weak to be detected. Indeed, while higher quality observations of [Si/H] and [Fe/H] confirm the absence of high N_{HI}, high Z systems, they do not show a deficiency of low N_{HI}, low Z systems (Prochaska & Wolfe 2001).

The solid curves indicate the neutral hydrogen column density in local hydrostatic and thermal equilibrium, computed using the method described in section 2. From top to bottom the curves correspond to dust-to-metals ratios of 0.1, 0.5 and 1.0 times the Galactic value respectively. Equilibrium solutions for pressure-confined gas clouds and self-gravitating clouds that contain a gravitationally significant amount of stars or dark matter are all located to the left of these curves. From the figure it is clear that the models can naturally account for the absence of high N_{HI}, high Z systems. A higher metallicity (dust-to-gas ratio) results in an increased H_2 formation rate and, because of the increased cooling via metals and H_2, a lower temperature. Both the higher H_2 formation rate and, via equation 1, the lower temperature contribute to the decrease in the maximum N_{HI}.

It is important to note that the maximum column densities are derived for single clouds, i.e., regions along the sight line over which the density is of the same order as the nearest (local) maximum, whereas the data points correspond to the integrated column densities of systems of clouds. Since essentially all DLA systems show substructure in their low-ionization metal lines, which are thought to trace the neutral hydrogen density, DLA systems must generally consist of collections of clouds. Unfortunately, the strength of the DLA line prohibits us from measuring the H I columns of the individual components. Hence, each observed N_{HI} value must be considered as an upper limit to the column density of the dominant component. If, for example, the strongest component would account for 50 percent of the neutral hydrogen column (and if all components had roughly the same metallicity), then the data point should be shifted by –0.3 dex along the N_{HI}-axis, which would place it comfortably to the left of most models.

Although the models clearly show that there should be an anticorrelation between metallicity and the maximum N_{HI}, the exact N_{HI} values are somewhat uncertain. First, although self-gravitating clouds will generally not be far from local hydrostatic equilibrium, there is no reason why they should be in exact equilibrium. Second, the derived column densities are sen-

sitive to the assumed intensity of the incident ionizing radiation. Figure 2b illustrates the effect of changing the amplitude of the UV/X-ray background. From top to bottom the curves correspond to models that use the same background radiation as was used in panel (A), but with the amplitudes multiplied by factors of 3, 1, and 1/3 respectively. The maximum N_{HI} increases if the background is stronger. Although these models are indicative of the uncertainty in the mean background radiation, the ionizing radiation could be stronger around DLA systems if they are located near regions of star formation or QSOs. In such systems higher N_{HI} values would be possible, although it should be noted that absorbers in these environments would likely be pressure confined.

Extrapolation of the solid curves in Fig. 2 suggests that large N_{HI} values are possible at zero metallicity. The reason is that for the low-Z models the $N_{HI}(n_H)$ curves flatten off very slowly with increasing n_H. The maximum N_{HI} is only reached when the density is higher than is typical of molecular clouds and when the characteristic mass of the cloud is lower than is typical of stars. The models used here are probably inadequate for systems which are nearly fully molecular. In any case, such systems are so compact that the cross section for interception by a random sight line is very small and they are highly unstable to star formation. Note also that the extreme low metallicity models are not relevant for DLA systems which all have $Z \gg 10^{-3}\ Z_\odot$. Nevertheless, it is instructive to look at a more robust quantity than the maximum N_{HI}, such as the N_{HI} corresponding to a fixed molecular fraction. The dashed curves in Fig. 2 show the N_{HI} at which the molecular fraction reaches 10 percent, much higher than is typical of DLA systems (e.g., Petitjean, Srianand, & Ledoux 2001). These curves do turn over at low Z. For example, $\log N_{HI} = 21.8$ at zero metallicity for the ionizing background used in Fig. 2a. Because the molecular fraction rises rather sharply to $f(\mathrm{H_2}) \sim 10^{-1}$ (see Fig. 1) due to a thermal instability, the curves corresponding to $f(\mathrm{H_2}) \sim 10^{-5}$ (not plotted) are similar to the dashed curves in Fig. 2.

Finally, the models cannot explain the apparent lack of $N_{HI} < 10^{21}$ cm^{-2} systems with $Z > Z_\odot$. If DLA systems with such high metallicities do occur in nature and if their cross sections and lifetimes are non-negligible, then it may be that a dust-induced selection bias still needs to be invoked to account for the absence of such systems from current samples.

4. CONCLUSIONS

One of the most basic observational findings is that all gas clouds seem to have neutral hydrogen column densities smaller than 10^{22} atoms per square centimeter. Studies of DLA systems have revealed that the maximum N_{HI} decreases with increasing metallicity. It was argued that dust-induced selection bias may not be a viable explanation for these observations. Instead, it was proposed that clouds with $N_{HI} > 10^{22}$ cm^{-2} do not occur because the clouds turn molecular before reaching such high column densities. Furthermore, because clouds with high molecular fractions are much more compact and short-lived than clouds with low molecular fractions, the latter provide a much larger cross section per unit mass for DLA absorption. The maximum H I column density is a decreasing function of metallicity, mainly because the formation rate of molecular hydrogen increases with the dust content of the system.

It was shown that models of self-gravitating gas clouds in local hydrostatic and thermal equilibrium, with a dust-to-metals ratio somewhat lower than the Galactic value, exposed to a model of the $z \sim 3$ UV/X-ray background radiation, can roughly account for the observed anticorrelation between the maximum N_{HI} value and metallicity. The assumption of pure gas clouds in hydrostatic equilibrium is conservative because self-gravitating clouds containing stars and/or dark matter, as well as clouds that are confined by external pressure, have lower column densities. The model works particularly well if one takes into account that observed DLA systems consist of multiple components, and that it is the integrated H I column density that is measured, whereas the model predicts the maximum N_{HI} for single gas clouds.

Finally, the models presented here predict that the molecular fraction increases with increasing N_H and dust-to-gas ratio (and thus metallicity if the dust-to-metals ratio is roughly constant), but is anticorrelated with the intensity of the incident UV radiation. These correlations could be uncovered observationally if a sample is constructed in which two out of the three parameters (N_H, Z, I_{UV}) are roughly constant. There could, however, still be considerable scatter in these relations if only a fraction of clouds are purely gaseous and self gravitating. The models also predict a strong anticorrelation between molecular fraction and temperature that is fairly insensitive to the values of the other parameters.

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